

Leptogenesis in a model with Friedberg-Lee symmetry

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Abstract

We study the matter-antimatter asymmetry through the leptogenesis mechanism in a specific model with the Friedberg-Lee (FL) symmetry. We relate the leptogenesis with the CP violating Dirac and Majorana phases in the Maki-Nakagawa-Sakata leptonic mixing matrix and illustrate the net baryon asymmetry of the universe in terms of these phases.

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I. INTRODUCTION

Neutrino oscillation experiments have indicated nonzero neutrino masses and mixings although they are not expected in the standard model (SM). One of the most plausible extensions of the SM to generate neutrino masses is the (type-I) seesaw mechanisms in which heavy right-handed Majorana neutrinos are introduced. This mechanism can explain not only the small neutrino masses but also the baryon asymmetry of the universe (BAU) via the leptogenesis mechanism [1, 2]. In the lepton sector, the leptogenesis is related to the CP violating Dirac and Majorana phases in the Maki-Nakagawa-Sakata (MNS) leptonic mixing matrix as well as some possible high energy phases [3]. It is clear that there is no leptogenesis if all phases vanish. However, since there are many high energy phases [4]¹, it is hard to make an explicit connection between the leptogenesis and the phases in the MNS matrix. In order to establish a simple relation between them, we need to reduce as many complex parameters as possible in the model. In Ref. [6], a family symmetry is used to minimize the number of arbitrary parameters in the Yukawa sector. Another possibility along this direction is to consider the so-called two-right-handed neutrino (2RHN) seesaw model [7], in which the number of parameters is less numerous than the ordinary seesaw model. In addition, spontaneous [8] and dynamical [9] CP violating approaches have been proposed.

In this Letter, we explore the leptogenesis mechanism in the model with the Friedberg-Lee (FL) symmetry [10] and directly relate it to the CP violating Dirac and Majorana phases in the MNS matrix. The FL symmetry is a translational hidden family symmetry for fermion mass terms. Several possible origins of the FL symmetry have been discussed in Ref. [11]. More detailed analyses of the symmetry have been given in Ref. [12]. The FL symmetry combined with a rotational symmetry has also been studied in Ref. [13].

As pointed out in Ref. [14], the introduction of the FL symmetry to the right-handed Majorana neutrinos suggests that there exists one massless right-handed neutrino with the absence of the corresponding column of the Dirac mass matrix in the basis of the diagonal right-handed Majorana mass matrix. As a result, the model can be regarded as

¹ In this Letter, we do not take into account the non-unitary effect of the MNS matrix. The discussion of the leptogenesis with the effect is given in Ref. [5].

the 2RHN seesaw model. This, in fact, motivates us to examine the leptogenesis in the context of the FL symmetry to see if it provides us with a testable seesaw and leptogenesis model.

This Letter is organized as follows. In Sec. II, we propose a model with the FL symmetry on both the right- and left-handed neutrinos. We also examine the allowed parameters based on the present neutrino oscillation data. In Sec. III, we consider leptogenesis and estimate the net baryon asymmetry of the universe (BAU) as a function of the Dirac and Majorana phases. We give the conclusion in Sec. IV.

II. TWISTED FRIEDBERG-LEE SYMMETRIC SEESAW MODEL

A. framework of model

We start with the conventional (type-I) seesaw framework with three right-handed Majorana neutrinos. The relevant Lagrangian is given by

$$-\mathcal{L} = Y_e \bar{L}_L H \ell_R + Y_D \bar{L}_L \tilde{H} \nu_R + \frac{1}{2} M_R \bar{\nu}_R^c \nu_R + h.c. , \quad (1)$$

where we have omitted family indices. We assume the diagonal charged lepton mass matrix and impose the twisted FL symmetry [13] only on neutrinos

$$\nu_{L(R)} \rightarrow S \nu_{L(R)} + \eta \xi , \quad (2)$$

where ξ is a non-local Grassmann parameter, η is a column vector of c-numbers, and S is the permutation matrix between the second and third families, given by

$$S = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} . \quad (3)$$

Here, we have adopted the specific combination $\eta \propto (-2, 1, 1)^T$ discussed in Ref. [13] so that the resulting neutrino mixing is tribimaximal. Due to the symmetry, the Majorana mass matrix takes the form

$$M_R = \begin{pmatrix} B/2 & B/2 & B/2 \\ B/2 & A+B & -A \\ B/2 & -A & A+B \end{pmatrix} . \quad (4)$$

In addition to the twisted FL symmetry in Eq. (2), we consider a Z_2 symmetry for the lepton doublet and charged singlet of the first family. Consequently, the Dirac mass matrix is given by

$$Y_D = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \alpha & -\alpha \\ 0 & -\alpha & \alpha \end{pmatrix}. \quad (5)$$

We note that without the Z_2 symmetry, Eq. (5) has the same form as Eq. (4). As a result, the model cannot reproduce a realistic neutrino mass spectrum because we focus on a scenario in which one of three light neutrinos is massless in this Letter.

The Majorana mass matrix in Eq. (4) can be diagonalized by the tribimaximal matrix [15]

$$V_{TB} = \frac{1}{\sqrt{6}} \begin{pmatrix} 2 & \sqrt{2} & 0 \\ -1 & \sqrt{2} & -\sqrt{3} \\ -1 & \sqrt{2} & \sqrt{3} \end{pmatrix}, \quad (6)$$

so that

$$\begin{aligned} D_R &\equiv (PV_{TB}^T)M_R(V_{TB}P) = \text{diag}(M_1, M_2, M_3) \\ &= \text{diag}(0, 3/2|B|, |2A + B|), \end{aligned} \quad (7)$$

where $P = \text{diag}(1, e^{i\phi_R/2}, 1)$ is a diagonal phase matrix of the right-handed Majorana neutrinos. In this basis, the Dirac mass matrix in Eq. (5) becomes

$$Y_R \equiv Y_D V_{TB} P = \sqrt{2}\alpha \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 0 & 1 \end{pmatrix}. \quad (8)$$

Note that α can be always real by suitable redefinitions of the left-handed leptons. As pointed out in Ref. [14], in this basis the right-handed neutrino of the first family can be regarded as a non-interacting massless neutrino. By omitting this field, we can move to 3×2 dimensional Dirac mass matrix basis and rewrite Eq. (8) as

$$Y_R = \sqrt{2}\alpha \begin{pmatrix} 0 & 0 \\ 0 & -1 \\ 0 & 1 \end{pmatrix}, \quad (9)$$

where $D_R = \text{diag}(M_2, M_3)$. The mass matrix of the light neutrinos is as follows

$$m_\nu = v^2 Y_R D_R^{-1} Y_R^T = \frac{2\alpha^2 v^2}{M_3} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & -1 \\ 0 & -1 & 1 \end{pmatrix}. \quad (10)$$

This matrix can be diagonalized by the tribimaximal matrix and has only one non-zero eigenvalue, m_3 . Thus, there are two interacting and one non-interacting massless neutrinos and no CP violating phase in the MNS matrix. Clearly, it is inconsistent with the experimental data of existing at least two massive light neutrinos.

In order to obtain a realistic model, we need to introduce symmetry breaking terms in Eq. (5), given by

$$Y_D = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \alpha & -\alpha \\ 0 & -\alpha & \alpha \end{pmatrix} + \begin{pmatrix} \frac{1}{4}(\Delta_1 + \Delta_2 + \Delta_3 + \Delta_4) & \frac{1}{2}(\Delta_1 + \Delta_4) & \frac{1}{2}(\Delta_2 + \Delta_3) \\ \frac{1}{2}(\Delta_1 + \Delta_3) & \Delta_1 & \Delta_3 \\ \frac{1}{2}(\Delta_2 + \Delta_4) & \Delta_4 & \Delta_2 \end{pmatrix}. \quad (11)$$

Note that the breaking terms violate both the permutation symmetry in Eq. (2) and the Z_2 symmetry, but preserve the translational symmetry so that the first family light neutrino remains massless. Note also that although we could introduce breaking terms for the Majorana mass matrix as well, we only focus on the effect from the Dirac mass matrix in the following discussions.

In the diagonal basis of the right-handed neutrinos, the Dirac mass matrix can be still regarded as an 3×2 dimensional matrix² and becomes

$$Y_R = \frac{1}{2} \begin{pmatrix} \frac{\sqrt{3}}{2}(\Delta_1 + \Delta_2 + \Delta_3 + \Delta_4)e^{i\phi_R/2} & -\frac{\sqrt{2}}{2}(\Delta_1 - \Delta_2 - \Delta_3 + \Delta_4) \\ \sqrt{3}(\Delta_1 + \Delta_3)e^{i\phi_R/2} & -2\sqrt{2}\alpha - \sqrt{2}(\Delta_1 - \Delta_3) \\ \sqrt{3}(\Delta_2 + \Delta_4)e^{i\phi_R/2} & 2\sqrt{2}\alpha + \sqrt{2}(\Delta_2 - \Delta_4) \end{pmatrix}. \quad (12)$$

In what follows, we consider the basis where α is real but Δ_i are complex and for simplicity assume $\Delta_1 \equiv \Delta \equiv |\Delta|e^{i\phi_\Delta}$ and $\Delta_2 = \Delta_3 = \Delta_4 = 0$. The mass matrix of the light neutrinos is given by

$$m_\nu = \frac{v^2}{M_3} \left[2\alpha^2 \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & -1 \\ 0 & -1 & 1 \end{pmatrix} + \frac{\alpha\Delta}{2} \begin{pmatrix} 0 & 1 & -1 \\ 1 & 4 & -2 \\ -1 & -2 & 0 \end{pmatrix} + \frac{\Delta'^2}{8} \begin{pmatrix} 1 & 2 & 0 \\ 2 & 4 & 0 \\ 0 & 0 & 0 \end{pmatrix} \right], \quad (13)$$

² This feature is ensured because the breaking terms still preserve the translational symmetry.

where the second and third terms are responsible for the deviations from the tribimaximal mixing with

$$\Delta'^2 = \Delta^2 \left[1 + \frac{3}{2} \frac{M_3}{M_2} e^{i\phi_R} \right], \quad (14)$$

while Δ and ϕ_R generate CP violation in the MNS matrix. Here, we define the MNS matrix as

$$V_{MNS} = V_{TB} \delta V \Omega = \frac{1}{\sqrt{6}} \begin{pmatrix} 2 & \sqrt{2} & 0 \\ -1 & \sqrt{2} & -\sqrt{3} \\ -1 & \sqrt{2} & \sqrt{3} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_\theta & s_\theta e^{-i\delta} \\ 0 & -s_\theta e^{i\delta} & c_\theta \end{pmatrix} \Omega, \quad (15)$$

where $s_\theta = \sin \theta$ ($c_\theta = \cos \theta$) with

$$\tan 2\theta = -\frac{\sqrt{6}(\alpha\Delta + \Delta'^2/4)e^{i\delta}}{(4\alpha^2 + 2\alpha\Delta + \Delta'^2/4)e^{2i\delta} - 3/8\Delta'^2} \equiv -\frac{\mathcal{I}e^{i\delta}}{\mathcal{J}e^{2i\delta} - \mathcal{K}}, \quad (16)$$

δ is the Dirac phase which has to satisfy

$$\delta = -\frac{i}{2} \ln \left[\frac{\mathcal{I}\mathcal{J}^* + \mathcal{I}^*\mathcal{K}}{\mathcal{I}^*\mathcal{J} + \mathcal{I}\mathcal{K}^*} \right], \quad (17)$$

to guarantee the right hand side of Eq. (16) to be real, and $\Omega = \text{diag}(1, e^{i\gamma/2}, 1)$ is a diagonal Majorana phase matrix. The mixing angles are given by

$$\sin^2 \theta_{13} = \frac{1}{3} s_\theta^2, \quad (18)$$

$$\sin^2 \theta_{12} \simeq \frac{1}{3} (1 - s_\theta^2), \quad (19)$$

$$\sin^2 \theta_{23} \simeq \frac{1}{2} - \frac{1}{6} s_\theta^2 - \frac{\sqrt{6}}{3} s_\theta c_\theta \cos \delta. \quad (20)$$

We note that our definitions of the Dirac and Majorana phases (δ and γ) are different from δ_{pdg} and γ_{pdg} of the standard parametrization proposed by the Particle Data Group [16]. The relations between them are given by

$$\cos \delta_{pdg} = \frac{c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 1/3(1 - 3s_{12}^2) - 3/2s_{13}^2 - \sqrt{2(1 - 3s_{13}^2)} s_{13} \cos \delta}{2s_{12}c_{12}s_{23}c_{23}s_{13}}, \quad (21)$$

$$\frac{\gamma_{pdg}}{2} = \frac{\gamma}{2} + (\delta - \delta_{pdg}), \quad (22)$$

where $s_{ij}(c_{ij})$ means $\sin \theta_{ij}(\cos \theta_{ij})$, respectively. The mass matrix in Eq. (13) is diagonalized by Eq. (15), leading to the masses of the light neutrinos to be

$$m_1 = 0, \quad (23)$$

$$m_2 = \frac{v^2}{M_3} \left| 4\alpha^2 s_\theta^2 e^{2i\delta} + \alpha\Delta(\sqrt{6}s_\theta c_\theta e^{i\delta} + 2s_\theta^2 e^{2i\delta}) + \frac{\Delta'^2}{4}(\sqrt{6}s_\theta c_\theta e^{i\delta} + s_\theta^2 e^{2i\delta} + 3/2c_\theta^2) \right|, \quad (24)$$

$$m_3 = \frac{v^2}{M_3} \left| 4\alpha^2 c_\theta^2 + \alpha\Delta(-\sqrt{6}s_\theta c_\theta e^{-i\delta} + 2c_\theta^2) + \frac{\Delta'^2}{4}(-\sqrt{6}s_\theta c_\theta e^{-i\delta} + 3/2s_\theta^2 e^{-2i\delta} + c_\theta^2) \right|. \quad (25)$$

The Majorana phase is given by

$$\gamma = -\gamma_2 + \gamma_3, \quad (26)$$

where

$$\sin \gamma_2 = \frac{\text{Im}[m_2]}{|m_2|}, \quad \sin \gamma_3 = \frac{\text{Im}[m_3]}{|m_3|}. \quad (27)$$

From Eqs. (17), (24), (25), (26) and (27), one can see that the Dirac and Majorana phases are originated from ϕ_R and ϕ_Δ .

B. low energy observables

Our model possesses two CP violating phases: ϕ_R and ϕ_Δ , plus four real parameters: α , $|\Delta|$, $|2A+B|$ and $|B|$. These six parameters can be fixed by six physical quantities. In our numerical calculations, we use the four best-fit values of the neutrino oscillation data with 1σ errors [17]

$$\Delta m_{21}^2 = (7.65_{-0.20}^{+0.23}) \times 10^{-5} \text{ eV}^2, \quad |\Delta m_{31}^2| = (2.40_{-0.11}^{+0.12}) \times 10^{-3} \text{ eV}^2, \quad (28)$$

$$\sin^2 \theta_{12} = 0.304_{-0.016}^{+0.022}, \quad \sin^2 \theta_{23} = 0.50_{-0.06}^{+0.07}, \quad (29)$$

as input parameters. The remaining two quantities are the masses of the heavy neutrinos, M_2 and M_3 . As we will discuss later, in order to account for the measured value of the BAU, they should be $\mathcal{O}(10^{10\sim 11})$ GeV, corresponding to $\alpha \sim 0.004$ and $|\Delta| \sim 0.002$. If $M_2 \gg M_3$, ϕ_R will be decoupled from low energy observables such as light neutrino masses, mixing angles and CP violating phases in the MNS matrix. Hence, the leptogenesis ends up depending on phases which cannot be observed by low energy experiments. On the other hand, in order to fit Eq. (28), M_3 cannot be much larger than M_2 and their ratio is

constrained by $M_3/M_2 \leq 6$. To illustrate our results, we take $M_3 = 8.0 \times 10^{10}$ GeV and $M_3/M_2 = 5$.

From Eqs. (18) and (20), one can see that the Dirac phase δ can be described by $\sin \theta_{23}$ and $\sin \theta_{13}$. Furthermore, from Eqs. (19) and (29), one obtains that

$$0.0073 < \sin^2 \theta_{13}. \quad (30)$$

By using the bound in Eq. (30) and 1σ values of $\sin^2 \theta_{23}$, we estimate the range of δ to be

$$62^\circ < \delta < 128^\circ. \quad (31)$$

In Fig. 1, we show the numerical result of δ as a function of $\sin^2 \theta_{23}$. As can be seen from the figure, the result is coincident with Eq. (31) very well. We note that the above results are insensitive to the mass scale of the right-handed Majorana neutrinos. In contrast, γ

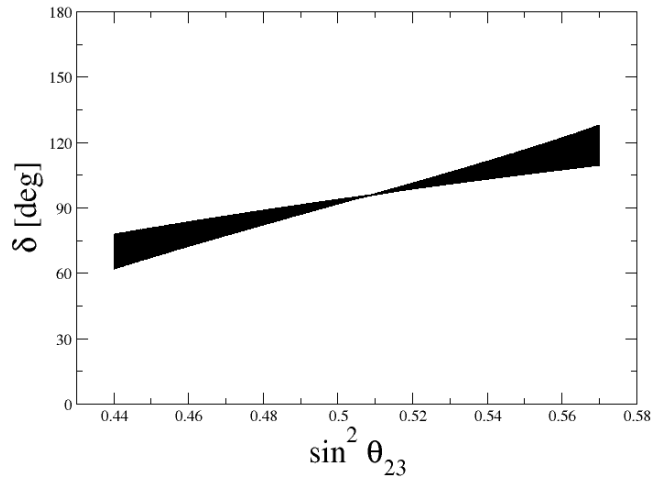


FIG. 1: The Dirac phase δ as a function of $\sin^2 \theta_{23}$ with $M_3 = 8.0 \times 10^{10}$ GeV and $M_3/M_2 = 5$.

has a wide allowed range and it could have an impact on the neutrinoless double β decay due to the effective Majorana mass

$$\langle m_{ee} \rangle = \left| \sum_{i=1}^3 m_i (V_{MNS})_{1i}^2 \right| \quad (32)$$

since the Dirac phase as well as individual neutrino mass can be determined within some ranges. In Fig. 2, we give γ as a function of the effective mass. Unfortunately, the

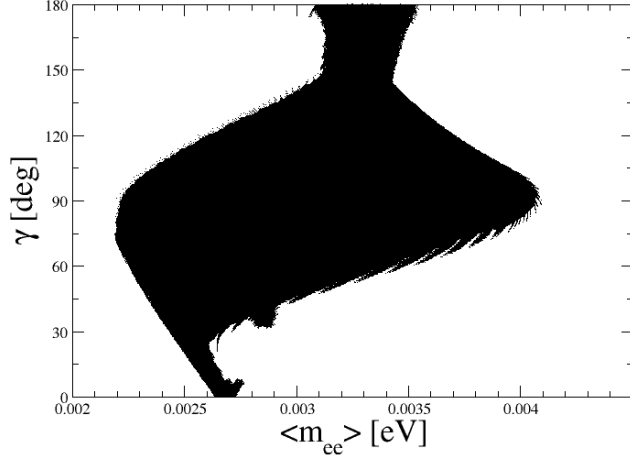


FIG. 2: γ as a function of the effective mass $\langle m_{ee} \rangle$ with $M_3 = 8.0 \times 10^{10}$ GeV and $M_3/M_2 = 5$.

predicted values of $\langle m_{ee} \rangle$ in our model are around $(2.2 - 4.1) \times 10^{-3}$ eV, which are too small to be detected in the current and upcoming experiments. For instance, the order of the present sensitivity at the CUORICINO experiment is 10^{-1} eV, while that of the proposed CUORE detector is 10^{-2} eV [19]. Nevertheless, we would like to emphasize that more dedicated experiments in future are needed in order to determine the Majorana phase.

Finally, we would like to briefly remark on the possibility to test our model. As our model predicts the novel relation $\sin^2 \theta_{13} \simeq 1/3 - \sin^2 \theta_{12}$ based on Eqs. (18) and (19), more precise determinations of mixing angles would provide us a chance to rule out or confirm the model in future. For instance, the smaller value of $\sin^2 \theta_{12}$, which is $\sin^2 \theta_{12} = 0.304^{+0.000}_{-0.016}$, results in $\sin^2 \theta_{13} = 0.0293 \sim 0.0453$ which is beyond the 1σ range given in Ref. [17]. On the other hand, the larger value $\sin^2 \theta_{12} = 0.304^{+0.022}_{-0.000}$ corresponding to $\sin^2 \theta_{13} = 0.0073 \sim 0.0293$ is well coincident with [17] and a recently proposed global analysis of the neutrino oscillation data [18].

III. LEPTOGENESIS

As discussed in the previous section, our model results in nonzero values of δ and $\sin \theta_{13}$ as shown in Eqs. (30) and (31). This means that the CP symmetry is always violated

in the lepton sector at 1σ level even if there is no Majorana phase γ . In this section, we consider the unflavored leptogenesis mechanism³ via the out-of-equilibrium decays of the heavy right-handed neutrinos. The CP violating parameter in the leptogenesis due to the i -th heavy neutrino decays is written as [2]

$$\varepsilon_i = -\frac{1}{8\pi} \sum_{j \neq i} \frac{\text{Im}[(Y_R^\dagger Y_R)_{ji}^2]}{(Y_R^\dagger Y_R)_{ii}} F\left(\frac{M_j^2}{M_i^2}\right), \quad (33)$$

where $i, j = 2$ or 3 , $F(x)$ is given by

$$F(x) = \sqrt{x} \left[\frac{1}{1-x} + 1 - (1+x) \ln \frac{1+x}{x} \right], \quad (34)$$

Y_R is the Dirac mass matrix in the diagonal basis of the right-handed neutrinos and charged leptons, given in Eq. (12), with the first (second) column referred as Y_{Rj2} (Y_{Rj3}). The dilution factor κ_i is approximately given by [21]

$$\kappa_i \simeq \frac{0.3}{r_i (\ln r_i)^{0.6}}, \quad (35)$$

where

$$r_i = \frac{\Gamma_i}{H|_{T=M_i}} = \frac{M_{pl}}{1.66\sqrt{g_*}M_i^2} \frac{(Y_R^\dagger Y_R)_{ii}}{16\pi} M_i \quad (36)$$

with $M_{pl} = 1.22 \times 10^{19}$ GeV and $g_* = 106.75$. The net BAU is found to be

$$\eta_B = \frac{n_B}{n_\gamma} = 7.04 \frac{\omega}{\omega - 1} \frac{\kappa_2 \varepsilon_2 + \kappa_3 \varepsilon_3}{g_*}, \quad (37)$$

where $\omega = 28/79$.

We note that, in general, the CP asymmetry depends on both ϕ_R and ϕ_Δ which are responsible for the Dirac and Majorana phases. In the followings, we first examine two extreme cases of (A) $\phi_R = 0$ and $\phi_\Delta \neq 0$ and (B) $\phi_R \neq 0$ and $\phi_\Delta = 0$, and then study the general case of (C) $\phi_R \neq 0$ and $\phi_\Delta \neq 0$. Since $\varepsilon_2 \gg \varepsilon_3$, we will only concentrate on ε_2 .

A. $\phi_R = 0$ and $\phi_\Delta \neq 0$

For $\phi_R = 0$ and $\phi_\Delta \neq 0$, the CP asymmetry in Eq. (33) can be simplified as

$$\varepsilon_2 = -\frac{1}{5\pi} \alpha \sin \phi_\Delta (2\alpha \cos \phi_\Delta + |\Delta|) F\left(\frac{M_3^2}{M_2^2}\right). \quad (38)$$

³ The importance of the flavor effects is discussed in Ref. [20].

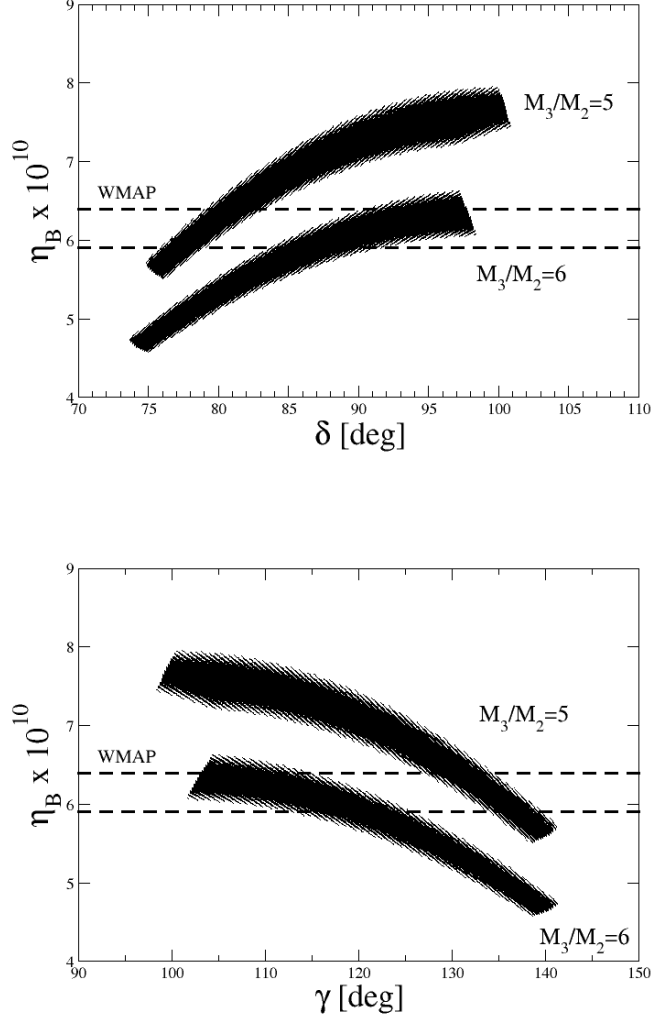


FIG. 3: η_B as a function of the Dirac phase δ (upper) or the Majorana phase γ (lower) for $\phi_R = 0$ and $\phi_\Delta \neq 0$ with $M_3 = 8.0 \times 10^{10}$ GeV, where the black regions correspond to $M_3/M_2 = 5$ and 6, respectively, and the present 1σ WMAP bound of $\eta_B = (6.1^{+0.2}_{-0.2}) \times 10^{10}$ is plotted as the dashed lines.

In this case, from Eqs. (17) and (27), one can see that ϕ_Δ is directly related to both Dirac and Majorana phases. As an illustration, in Fig. 3, we estimate the net BAU in terms of the Dirac phase δ (upper) and the Majorana phase γ (lower) with $M_3 = 8.0 \times 10^{10}$ GeV, where the regions correspond to $M_3/M_2 = 5$ and 6, respectively, and the present WMAP bound of $\eta_B = (6.1^{+0.2}_{-0.2}) \times 10^{10}$ [22] at 1σ is plotted as the dashed lines. From the figure, to obtain the measured BAU at 1σ , we find that $\delta \sim 76^\circ - 83^\circ$ ($84^\circ - 98^\circ$) and

$\gamma \sim 127^\circ - 140^\circ$ ($102^\circ - 125^\circ$) for $M_3/M_2 = 5$ (6). The allowed ranges of the phase parameters for $M_3/M_2 = 5$ are smaller than those for $M_3/M_2 = 6$.

B. $\phi_R \neq 0$ and $\phi_\Delta = 0$

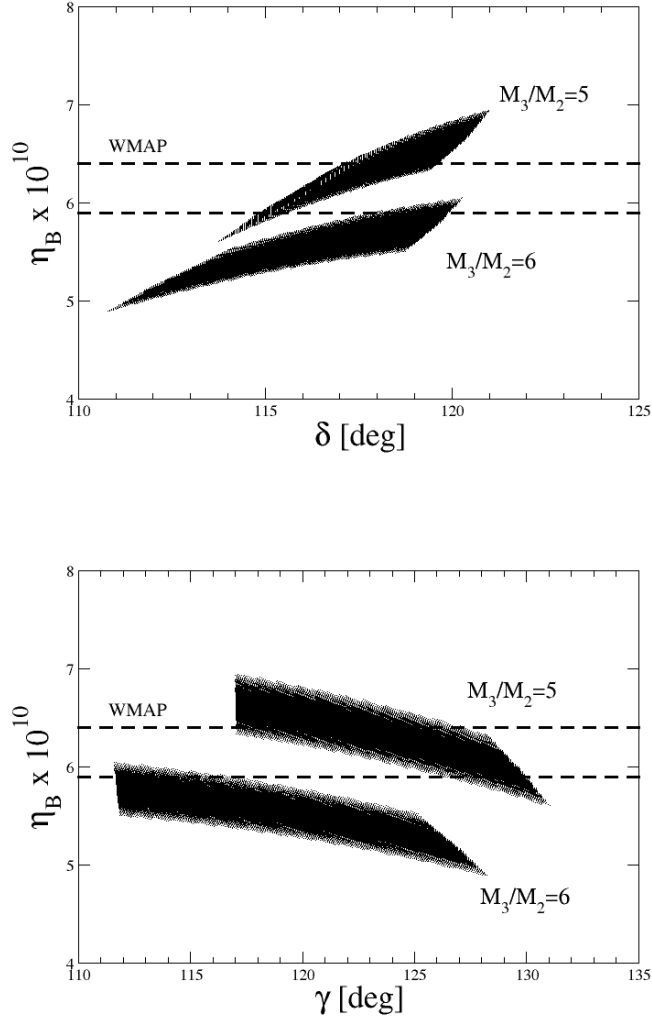


FIG. 4: Legend is the same as Fig. 3 but for $\phi_R \neq 0$ and $\phi_\Delta = 0$.

Similarly, for $\phi_R \neq 0$ and $\phi_\Delta = 0$, the CP asymmetry is given by

$$\varepsilon_2 = -\frac{1}{20\pi} \sin \phi_R \left[\frac{|\Delta|^2}{16} + (|\Delta| + 2\alpha)^2 \right] F \left(\frac{M_3^2}{M_2^2} \right), \quad (39)$$

where the phase ϕ_R is responsible for both Dirac and Majorana phases. In Fig. 4, we display η_B as a function of δ (upper) or γ (lower) similar to Fig. 3. As seen from the figure, at 1σ level, almost all phase parameters in the plane for $M_3/M_2 = 6$ are ruled out by the WMAP data of the BAU, whereas for $M_3/M_2 = 5$, δ and γ are found to be around $115^\circ - 120^\circ$ and $117^\circ - 130^\circ$, respectively.

C. $\phi_R \neq 0$ and $\phi_\Delta \neq 0$

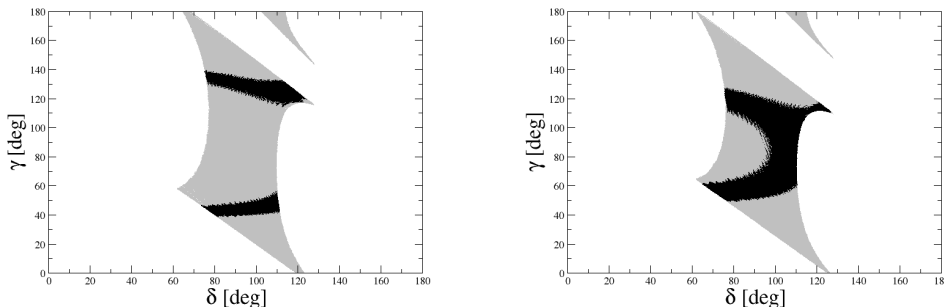


FIG. 5: Allowed regions in $\delta - \gamma$ plane with $M_3 = 8.0 \times 10^{10}$ GeV and $M_3/M_2 = 5$ (left) and 6 (right), where the gray and black regions correspond to those fitted by the neutrino oscillation and WMAP data at 1σ , respectively.

For the general case of $\phi_R \neq 0$ and $\phi_\Delta \neq 0$, instead of showing a much more complex analytic formula of ε_2 , we only give the numerical results. In Fig. 5, we show the allowed regions in $\delta - \gamma$ plane with $M_3 = 8.0 \times 10^{10}$ GeV and $M_3/M_2 = 5$ (left) and 6 (right), where the gray and black regions represent to those fitted by the neutrino oscillation and WMAP data, respectively. In contrast with the previous cases of (A) and (B), two narrow ranges of γ and a wide range of δ are allowed for $M_3/M_2 = 5$, while those for $M_3/M_2 = 6$ are continuous and broad.

IV. CONCLUSION

We have studied the BAU through the leptogenesis mechanism in the model with the FL symmetry. We have tried to make a connection between the leptogenesis and the

CP violating Dirac and Majorana phases in the MNS matrix. In particular, we have demonstrated that there exists a wide range of these phases to achieve the measure BAU, allowed by the neutrino data.

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